

**PERIPHERAL INTERACTIONS : QUASI PROJECTILE-PARTICLE AND PARTICLE-PARTICLE CORRELATIONS**

G. BIZARD

*Laboratoire de Physique Corpusculaire, ISMRA Université,  
F-14032 Caen Cedex, France*

Résumé : Les résultats expérimentaux concernant les coïncidences quasi-projectile-particule et particule-particule dans les interactions entre ions lourds à énergie intermédiaire sont passés en revue et leur interprétation est discutée.

Abstract : Quasi projectile-particle et particule-particule coincidence measurements in intermediate energy heavy ions interactions are reviewed and their interpretation is discussed.

**I - INTRODUCTION**

The purpose of this talk is to discuss the interest, for a better understanding of peripheral reactions in the intermediate energy domain, of light particles coincidence measurements.

It is customary to begin such a review by defining what are the intermediate energies and explain why we need to introduce this concept.

We call intermediate energies a domain which goes roughly from 10 MeV per nucleon to 100 MeV per nucleon and which bridges two regions where the heavy ions physics is quite well understood but radically different.

Under 10 MeV/u, the heavy ions reactions are dominated by collective effects<sup>(1,2)</sup>.

Let us consider for instance a nucleus-nucleus interaction at 10 MeV/u. The de Broglie wave length associated with a nucleon belonging to the projectile is 3 fm (we have supposed equal masses for the projectile and target nuclei). This is notably larger than the mean internucleon distance inside the nucleus (1.2 fm) and so every incident nucleon 'sees' several nucleons of the target. In addition, Pauli exclusion principle hinders most of the individual nucleon nucleon interactions : this low energy region is the domain of mean field theory and one body dissipation processes. The interaction time is generally long enough to allow equilibration of the internal degrees of freedom. Central collisions will lead to fusion, more peripheral collisions mainly to deep inelastic processes and very peripheral collisions to transfer reactions. Above 100 MeV/u, the conditions are completely different<sup>(3)</sup> : for a 100 MeV/u nucleus-nucleus collision, the de Broglie wave length associated with a nucleon of the projectile is now .9 fm which is close to the internucleon distance : every incoming nucleon can see now individually the nucleons of the target and as the Pauli blocking becomes less and less effective when the energy increases, the high energy heavy ion reactions will be governed by the nucleon nucleon interactions. Central collisions will lead to explosions and peripheral interactions to fragmentation. The interaction time is not large enough to attain equilibration and some non equilibrated phenomena could be expected such as hot spots or compression effects.

I shall restrict myself in this paper to peripheral interactions. That is to say for experimentalists, either reactions in which a nucleus with a mass and a velocity close to that of the projectile is detected or interactions characterized by a low light particle multiplicity.

The transition between low energy deep inelastic and transfer processes and high energy fragmentation has to take place somewhere between 10 and 100 MeV/u. It has been thought at first that even at energies as low as 20 MeV/u the high energy fragmentation was already established<sup>(4)</sup>, but it was rapidly recognized that this was not so simple and that we are facing intermediate processes with some characters reminiscent from the low energy regime and other similar to high energy reactions. At high energy, the momentum distributions of the fragmentation products are well described by gaussian shapes :

$$d^3\sigma/dp^3 \propto e^{-p_{\perp}^2/2\sigma^2} e^{-(p_{\parallel}-p_{\parallel}^0)^2/2\sigma^2}$$

$\sigma^2$  can be expressed in terms of the masses  $A_P$  of the beam and  $A_F$  of the quasi-projectile fragment :

$$\sigma^2 = \sigma_0^2 A_F (A_P - A_F)/(A_P - 1)$$

The meaning of the constant  $\sigma_0$  can be understood in two different ways<sup>(5)</sup> :

i) In a first model, the projectile dissociates instantaneously, the fragmentation products distribution reflects the internal distribution of the nucleons inside the projectile and  $\sigma_0$  can be related to the Fermi energy :  $\sigma_0 = p_F/\sqrt{5}$  ;

ii) Alternatively, after the collision, the excited quasi-projectile reaches equilibrium at temperature  $T$  and then dissociates.

$\sigma_0$  is then related to  $T$  by :

$$\sigma_0 = \frac{A_P - 1}{A_P} m_0 T \quad (m_0 = \text{proton mass})$$

Above 100 MeV/u, the fragmentation experimental results are compatible with a unique value of  $\sigma_0$  around 90 MeV/c. An example can be seen in figure 1 which shows the  $\sigma_0$  extracted for different quasi projectile from 213 MeV/u Ar+C data<sup>(6)</sup>.

Between 10 and 100 MeV/u, the situation is different (7,8,9,10,11, 12,).

- The momentum distributions of the fragmentation products are no more pure gaussians (see fig. 2).
- The best  $\sigma_0$  is found to depend on the incident energy (fig. 3);
- For a given incident energy,  $\sigma_0$  depends on the mass of the fragment (fig. 4).

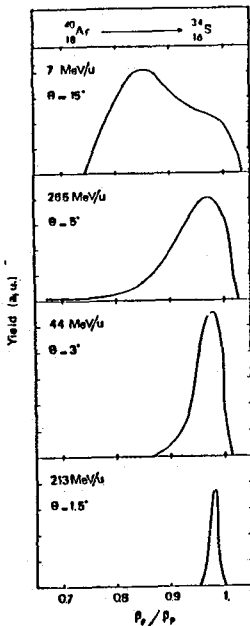


FIGURE 2: Evolution with energy of the  $^{34}\text{S}$  velocity spectrum near the grazing angle in Ar induced reactions<sup>(8)</sup>.

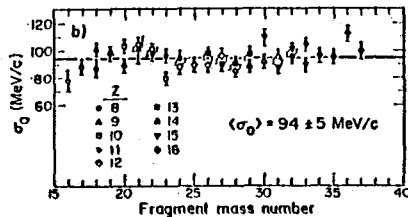


FIGURE 1: Evolution of  $\sigma_0$  as a function of the quasi projectile mass in the 213 MeV/u Ar+C system<sup>(6)</sup>.

FIGURE 5 : Schematic illustration of the different processes that may contribute to the formation of projectile like fragments<sup>(10)</sup> :

- a) Prompt fragmentation;
- b) Sequential fragmentation;
- c) Transfer reaction.
- d) Transfer reaction followed by sequential emission.



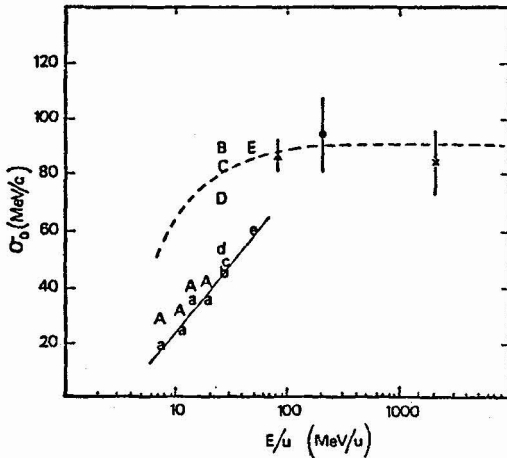


FIGURE 3: Variation of  $\sigma_0$  with incident energy(25).

— Transfer component  
 ---- Fragmentation component

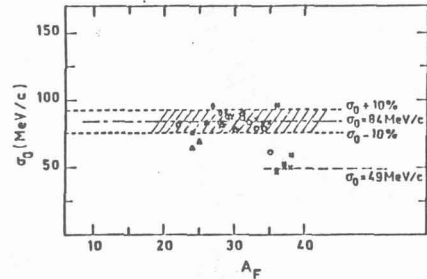


FIGURE 4 : Evolution of  $\sigma_0$  as a function of the quasi projectile mass in the 27 MeV/u Ar+Zn system(19).

Although some of these anomalies can be explained by inclusion of Pauli blocking (13,14,15), coulombian effects (16) binding energy effects (17), it is clear that high energy models fail to describe intermediate energy peripheral reactions. I shall try in the first part of my talk to show how coincidence measurement between quasi projectile and light particles may help to clarify some aspects of the peripheral reactions in the intermediate energy domain, namely :

- i) The competition between transfer and fragmentation ; ii) the competition between prompt and sequential fragmentation ; iii) The possible onset of the participant spectator process ;
- In the second part of my talk I shall discuss the results of light particle correlations experiments.

## II - QUASI PROJECTILE - LIGHT PARTICLE COINCIDENCES

A schematic illustration of the different processes that may contribute to the projectile like fragments is given in figure 5(10). One may observe pure transfer reactions pure fragmentation reactions or mixed processes.

### II-1 : The competition between transfer and fragmentation :

Considering the Fermi spheres in the momentum space of the projectile and target nuclei for different incoming energies (18), we can see that transfer processes are expected to be present up to 100 MeV/u (fig. 6).

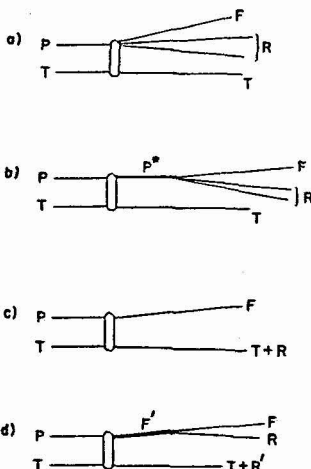


FIGURE 5.

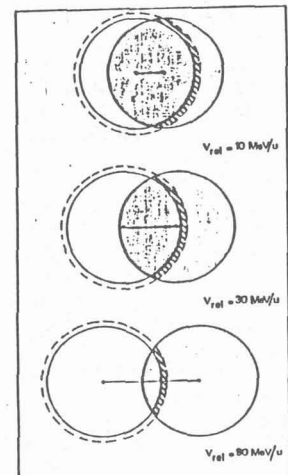


FIGURE 6 : Fermi spheres for different relative velocities of two colliding heavy ions(8). The dashed zone is accessible for transfer reactions.

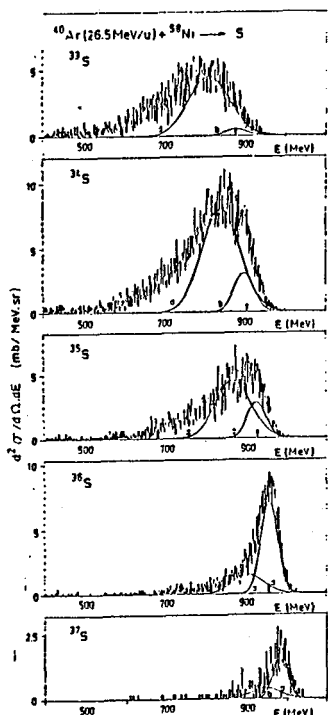


FIGURE 7 : Transfer and fragmentation contributions for sulfur isotopes produced in 27 MeV/u Ar+Ni reaction (25).

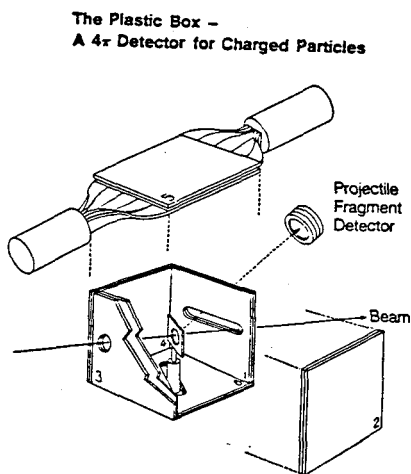


FIGURE 8 : The plastic box (27).

Direct and indirect proofs that we have to count with transfer reactions in peripheral reactions at intermediate energies are numerous in inclusive experiments :

- variation of  $\sigma_0$  with the mass of the quasi projectile (19,20) (fig. 4) ;
  - Direct observation of masses larger than that of the projectile such as  $^{41}\text{Ca}$  and  $^{41}\text{K}$  in 44 MeV/u  $^{40}\text{Ar}+^{27}\text{Al}$  reaction (21), N in 86 MeV/u  $^{12}\text{C}+^{12}\text{C}$  (22) or  $^{15}\text{O}$  in 60 MeV/u nitrogen induced reactions on various targets (23). Transfers have also been identified by high resolution measurement in the  $^{16}\text{O}+^{208}\text{Pb}$  system at 50 MeV/u (24) ;
  - Careful analysis of the energy spectra showing that two contributions (fragmentation and transfer) are needed (25). Figure 7 shows such a decomposition for some nuclei produced in the 27 MeV/u  $^{40}\text{Ar}+^{58}\text{Ni}$  reaction.
- But the best way to separate transfer and fragmentation is of course to perform exclusive experiments.

Several techniques have been used :

- streamer chamber (26)
- plastic box which surrounds almost completely the target with six plastic scintillators (27). Transfer reactions have easily identified : they correspond to reactions for which no signal can be found in the walls of the box : with this technique, transfer probabilities have been measured for the  $^{20}\text{Ne}+^{197}\text{Au}$  system at 11 and 17 MeV/u (28).
- Quite similar in their principles are the experiments performed with forward multi-detectors. The plastic wall in operation at GANIL (29,30) is an assembly of 96 plastic scintillators covering entirely the angular range  $3^\circ$ - $30^\circ$  with respect to the beam (31). The experimental set up is shown in figure 9. The particles detected in the wall are identified in charge and their velocity is measured. Transfer reactions correspond to 0 multiplicity events (fig. 10), but here we have to take care of particles escaping either in the central hole of the wall or with angles larger than  $30^\circ$ . Raw data have been corrected for these two effects and angular distribution of transfer probabilities have been determined for the 35 MeV/u Ar+Ag system (fig. 11). The importance of transfer reactions has also been recognized in similar experiments conducted on the 40 MeV/u  $^{14}\text{N}+^{197}\text{Au}$  (32) and 35 MeV/u  $^{84}\text{Kr}+^{93}\text{Nb}$  (33) systems.

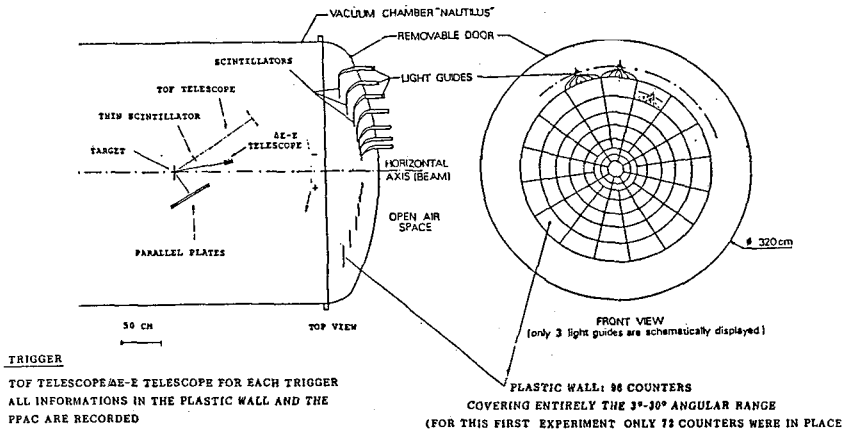


FIGURE 9 : Experimental set up used in the 35 MeV Ar+Ag and Ar+Au experiments (29,56,57). Projectile-like fragments are detected by the E-ΔE telescope. Target residues are detected either by the first element of the E-ΔE telescope or by the TOF telescope. Fission fragments are detected in coincidence by the TOF telescope and the parallel plates detector. Finally, coincident forward emitted light particles are identified in the plastic wall<sup>(29)</sup>.

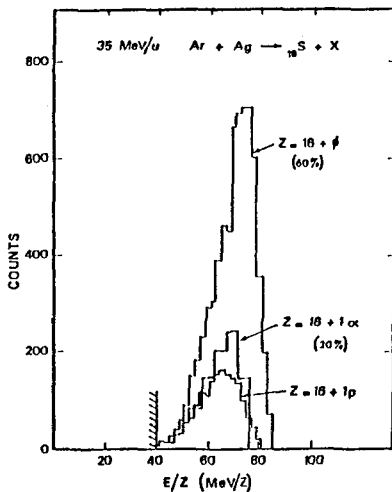


FIGURE 10 : Energy spectra of the  $Z=16$  quasi projectile produced in the 35 MeV/u Ar+Ag system in coincidence with no particle, or an alpha particle, or a proton<sup>(29)</sup>.

- Another possibility to separate transfer from fragmentation consists of using a  $4\pi$  neutron detector to measure the total energy removed from the target by neutron evaporation : transfer reactions (from the projectile to the target) are associated with large excitations of the target, whereas projectile break up leads to small excitation of the target<sup>(34)</sup>.

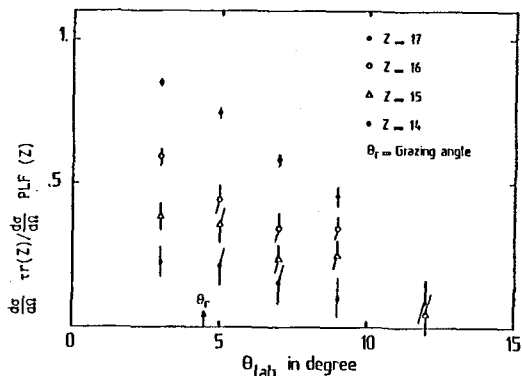


FIGURE 11 : Angular distribution of the transfer probabilities for the 35 MeV/u Ar+Ag system<sup>(29)</sup>.

- Transfer reactions can also be identified by detecting in coincidence a quasi projectile and the gamma emitted by the target. This technique has been used to isolate transfer reactions in the 30 MeV/u N+Tm and N+Yb systems<sup>(35)</sup>.

The results of these experiments have shown that up to three charges away from the projectile the contribution of transfer reactions in the 'fragmentation peak' remains important at intermediate energies (fig. 12 and 13). Several authors have proposed models to calculate the transfer cross sections in the intermediate energy domain<sup>(36,37,38,39,40)</sup> but a complete description of the data would imply a good knowledge of the high momenta tail of Fermi distribution of the nucleons in the nuclei<sup>(37)</sup>.

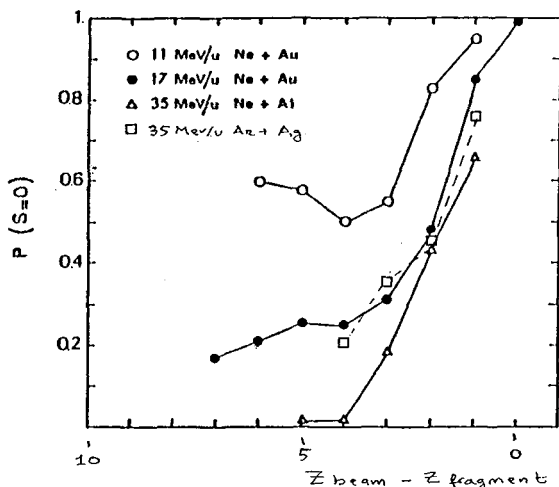


FIGURE 12 : Energy dependance of the transfer probability for different outgoing ejectiles in Ne and Ar induced reactions.

## II-2 : Fragmentation and mechanisms :

Once the pure transfer reactions have been isolated, one has to identify the fragmentation mechanisms (see fig. 5) :

- sequential break up where the projectile dissociates outside the field of the target ;
- prompt break up for which the dissociation takes place in the field of the target ;
- mixed processes for which one of the preceeding mechanisms is accompanied by transfer reactions.

The importance of pure transfer reactions suggests that most of fragmentations could belong to the last category. This is confirmed by the exclusive experiment performed at GANIL on the 35 MeV/u Ar+Ag system<sup>(29)</sup> :

The total charge intercepted in a forward cone of 30 degrees aperture (see figure 9) does not show any enhancement for the value of the beam charge, indicating that the fragmentation is accompanied by nucleons exchange between target and projectile or quasi projectile (fig. 14).

Another indication that the target does not stay passive during the fragmentation can be found in the slowing down of the quasi projectile fragments as compared to the beam velocity (see fig. 10).

To learn more about the fragmentation process and distinguish between sequential and prompt break up a careful analysis of the correlations between quasi projectile and

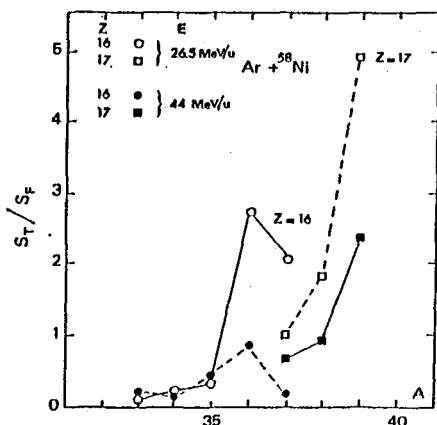


FIGURE 13 : Transfer cross section to fragmentation cross section ratio for S and Cl isotopes produced in Ar+Ni reaction<sup>(25)</sup>.

light particles has to be performed. This has been done for instance in an experiment conducted at SARA on the 35 MeV Ne+Al system<sup>(42)</sup>. The apparatus is quite similar to the one used at GANIL in the 35 MeV Ar+Ag experiment : here again the forward particles are identified in a scintillator wall (19 elements covering from 2 to 10 degrees). The correlation between <sup>16</sup>O fragment and alpha particles shows clearly that most of the incident neon nuclei dissociate outside the field of the target :

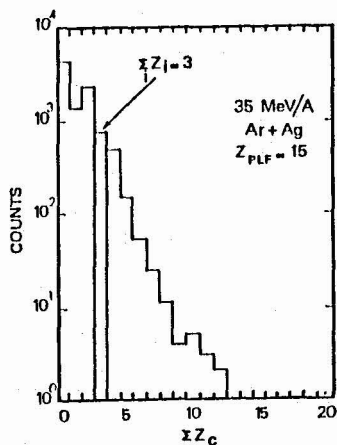


FIGURE 14 : Total charge in the plastic wall in coincidence with a  $Z=15$  quasi projectile in the 35 MeV/u Ar+Ag system<sup>(41)</sup>.

an unambiguous signature of this process is the observation for a given detection angle of two families of events corresponding respectively to forward and backward emission of the alpha particle in the system of the excited neon (fig. 15). However an important percentage of the events (40%) cannot be explained by sequential break up and are thus candidates for a prompt break up mechanism. Other experiments on light ions have also looked for the presence of a prompt break up component<sup>(43)</sup>. The 15 MeV/u Ne+Au<sup>(44)</sup>, 20 MeV/u Cl+Ta<sup>(45)</sup>, 12 MeV/u O+C<sup>(46)</sup> reactions exhibit only the sequential component. On the other hand, various indications of direct break up have been found in other systems :

- Li+Sn<sup>(47)</sup> and Li+Pb<sup>(43)</sup> at 10 MeV/u ;
- N+Al at 30 MeV/u<sup>(48)</sup> ;
- <sup>20</sup>Ne+Nb<sup>(49)</sup> and <sup>22</sup>Ne+Nb<sup>(50)</sup> at 30 MeV/u.

However, more of these difficult experiments have to be undertaken with heavier projectiles and at different energies before we could have a good idea of the fragmentation mechanisms at intermediate energy.

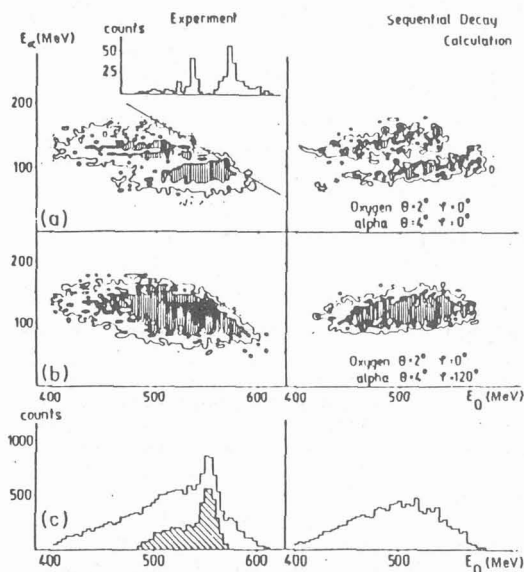


FIGURE 15 : <sup>16</sup>O-alpha coincident events in the  $E_\alpha$ - $E$  oxygen plane<sup>(42)</sup>.

### II-3 : Do we see the onset of participant spectator mechanism ?

The participant spectator model<sup>(51,52,53)</sup> has been successful in describing the high energy peripheral interactions. It predicts in the final state the presence of two fragments, remnants of the incident nuclei (a quasi projectile moving with a velocity close to that of the beam and a quasi target almost at rest) and of a hot expanding participant zone moving with approximately half the incident velocity.

Inclusive spectra of light particles emitted in intermediate energy heavy ion collisions, when analysed in terms of moving sources, show usually the presence of an intermediate source which could be attributed to an eventual participant zone<sup>(54)</sup>. Moreover, a fragment-fragment coincidence experiment on the 44 MeV <sup>40</sup>Ar+<sup>27</sup>Al system is in agreement with an abrasion model<sup>(9,55)</sup>.

However, the best way to identify

a participant spectator process would be to detect in an exclusive experiment the projectile like and target like fragments as well as light particles belonging to the participant zone. Such a decisive experiment has not been made yet but semi-exclusive data are now available on Ar+Ag and Ar+Au systems at 35 MeV/u : slow heavy residues and fission fragments have been detected in coincidence with forward light nuclei and particles intercepted by the plastic wall<sup>(56,57)</sup>. Only the most peripheral events can be described by transfers from the projectile to the target. The other events could be created by an abrasion process, but the standard participant-spectator model cannot describe the data : the heavy fragment velocities are

too large to be compatible with the hypothesis of a purely spectator target. However, if one includes reabsorption of some of the participants by the projectile and the target<sup>(58)</sup>, the velocity and angular distributions of the fragments can be understood<sup>(59)</sup>. We have compared the velocity spectra of light particles detected in coincidence with target like and projectile like fragments with the predictions of this modified participant spectator model. The shape of these spectra seems to be incompatible with the presence of nucleons originating from a thermalized participant zone : the low energy component of the light particles velocity spectrum is in quite good agreement, in shape, position and magnitude with the predicted evaporation from the target but the participant protons obviously cannot fit in the experimental distribution (fig. 16). Of course, the energy of 35 MeV/u is somewhat low to look for a participant spectator process and similar experiments and analyses have to be done at higher energies.

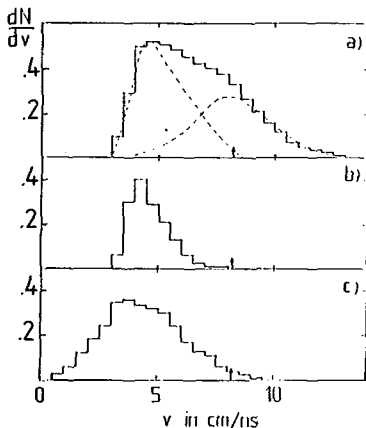


FIGURE 16 : Velocity spectra of forward light particles in coincidence with a low target-like fragment and a quasi projectile in the 35 MeV/u Ar+Au system<sup>(59)</sup>.

a) Experimental 'proton' velocity spectrum. This distribution includes free protons as well as protons contained in alpha particles. The arrow indicates the beam velocity. A crude decomposition in high velocity and low velocity components has been made, with respective multiplicities of 1.2 and 1.5 per event. b) and c) Predicted proton yields in the plastic wall in the hypothesis of an abrasion ablation process. The excited target and the heated participant zone are supposed to evaporate only nucleons. Figure 16b and 16c shows respectively the protons evaporated by the target (multiplicity = .85) and those originating from the participant region (multiplicity = 1.6).

#### II-4 : Conclusion on quasi projectile-particle coincidences

Fragment/light particle coincidence experiments are a good tool to study the peripheral interactions in the intermediate energy region.

We have seen that :

- transfer and fragmentation reactions are in competition ;
- the fragmentation process includes sequential dissociation as well as direct break up ;
- concerning the participant/spectator process, no definitive conclusion can be reached : this model seems necessary to explain some fragment/fragment experiments (54,33) ; it succeeds also in predicting the characteristics (mass, velocity, angle) of the fragments in the 35 MeV/u Ar+Au system, but the eventual participant nucleons are not seen.

Though similar in various aspects to high energy heavy ion reactions, intermediate energy peripheral collisions cannot be described by high energy models. A new generation of promising models including nucleon nucleon interactions together with mean field effects have appeared<sup>(60,61)</sup>. A detailed confrontation of these models with physical reality will require new experiments as exclusive as possible.

### III - TWO PARTICLE CORRELATIONS

Various models elaborated to explain particle emission in intermediate energy heavy ion reactions are based on the hypothesis of the existence of localized sources constituted of a subset of nucleons and characterized by their spatial extension, their mean life and their temperature<sup>(62)</sup>. Light particle correlations at small relative momentum (interferometry) provide a powerful technique to reach these parameters. First, I shall recall briefly the basic ideas and formalism of the interferometry technique. Then, the experimental correlation results in the intermediate energy domain, for small and large relative momenta, will be reviewed.



### III-1 : Interferometry : ideas and formalism

The interferometry was first introduced to measure the spatial extension of stellar objects<sup>(63)</sup>. The application of this method to nuclear physics was then proposed by Kopilov<sup>(64)</sup>. The idea relies on quantal properties of identical particles : the correlation function is expected to show deviation from its mean value when both particles belong to the same phase space cell, this deviation being positive (enhancement) for identical bosons and negative (decrease) for identical fermions. The width of the positive or negative peak is related to the probability to find both particles at the same point of the phase space : it provides therefore a mean to evaluate the space-time extension of the object which emits the two particles. Assuming for instance a source of radius  $r$  and lifetime  $t$ , the correlation function writes :

$$R = \pm \frac{[J_1(q_{\perp} r)/q_{\perp} r]^2}{1 + q_0^2 t^2}$$

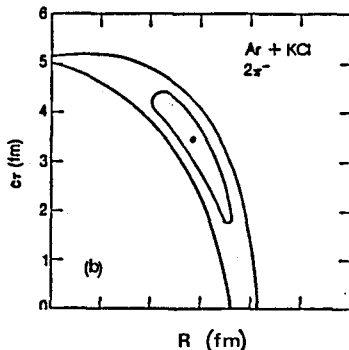
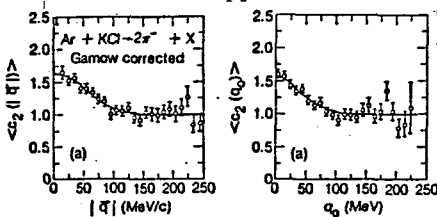
where the  $\pm$  sign refers to the nature of the particles (+ for bosons, - for fermions),  $q_{\perp}$  is their transverse relative momentum,  $q_0$  their relative energy and  $J_1$  the Bessel function of first kind. Calling  $\vec{k}_1$ ,  $\vec{k}_2$ ,  $\varepsilon_1$ ,  $\varepsilon_2$ , the momenta and energies of the two particles, we have :

$$q_{\perp} = |\vec{k}_1 - \vec{k}_2| \quad q_0 = \varepsilon_1 - \varepsilon_2$$

Experimentally, the correlation function is related to the probabilities of coincidence ( $P(\vec{k}_1, \vec{k}_2)$ ) and single ( $P(\vec{k})$ ) measurements :

$$R = \frac{P(\vec{k}_1, \vec{k}_2)}{P(\vec{k}_1)P(\vec{k}_2)} - 1$$

This technique has been applied successfully to  $\pi\pi$  correlations in high energy heavy ions collisions<sup>(65)</sup> (figure 17), but of course  $\pi\pi$  correlations are not appropriate to study the intermediate energy domain and we have to adapt the method to pp correlations. With pp correlations we have to consider the final state interaction :



- coulombian repulsion for small  $q_T$  (this effect is also present for  $\pi\pi$  correlations) ;
- s wave nuclear attraction which induces an enhancement around  $q_{\perp} = 20$  MeV/c in the pp correlation function.

However, the intensity of the  $q_{\perp} = 20$  MeV/c bump is related to the probability of the two protons to interact, therefore to their probability to be emitted close to one another in the space time. So the intensity of the final state interaction measures the extension of the emitting source (figure 18).

Once, this is established, there is no reason to stick to identical particles. The method can be extended to whichever couple of particles we want, provided their final state interaction is strong enough to allow a meaningful measurement<sup>(66)</sup>. This is obviously the case for some systems like  $\alpha d$  or  $\alpha p$  which can form particle unstable resonances (figure 19).

Moreover, the detection of resonances can allow a measurement of the temperature of the emitting zone. For a given size and lifetime of this emitting zone the probability to form a resonance depends on the distribution law of the

FIGURE 17 : Correlations between two negative pions emitted in the 1.8 GeV/u Ar+KCl reaction<sup>(65)</sup>. a) Projected correlation functions. b) Contours for the 68% and 95% confidence levels for joint determination of  $r$  and  $t$ .

relative momentum of the constituents of the resonance.

Therefore, if the momentum distributions of the particles emitted by the hot zone are determined by a unique parameter, for example the temperature for a thermalized emitter, the probability to detect a resonance is directly related to this parameter.

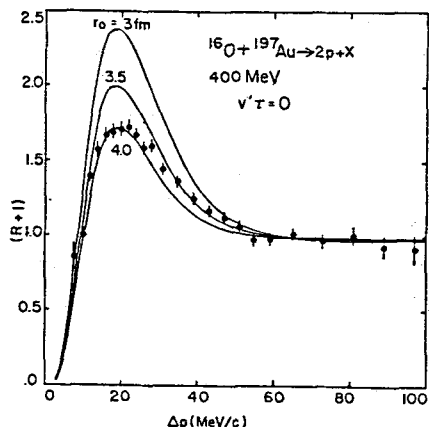


FIGURE 18 : Correlation function between two protons emitted in the 25 MeV/u O+Au reaction(70).

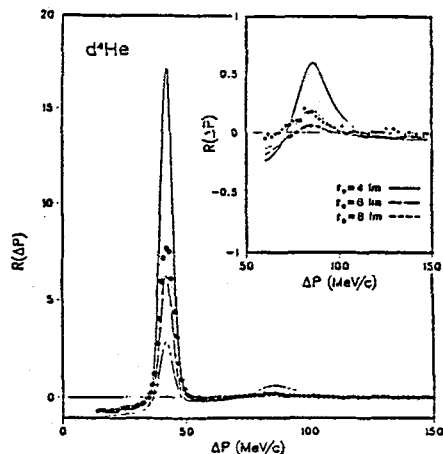


FIGURE 19 : Alpha-deuteron correlation function in the 60 MeV/u Ar+Au reaction(79).

### III-2 : Interferometry : experimental results

Small relative momentum correlations have been measured for different couples of particles in the following intermediate energy reactions :

- Ne+Au at 20 MeV/u(67)
- O+C and O+Al at 25 MeV/u(68)
- O+Au at 25 MeV/u(69,70)
- N+Au at 35 MeV/u(71,72)
- Ar+Au at 60 MeV/u(73,74,75,76,77,78,79,80)
- C+(C,Al,Au) at 85 MeV/u(81)

We shall refer also, for comparison, to the 400 MeV/u Ca+Ca and Nb+Nb correlation measurements(82).

The results of these experiments are generally analyzed in terms of incoherent emission by a hot localized source, but, before going in the details of the interpretation, let us point out two exceptions :

- in the 20 MeV/u Ne+Au experiment which is presented in a contribution to this conference(67), the authors have measured the forward alpha-alpha correlations and have found them compatible with a sequential decay of the quasi-projectile.
- the p-p correlations in the 25 MeV/u O+C and O+Al reactions can be explained by a thermal emission of  $^2\text{He}$  by the compound nucleus. However, the authors exclude this type of interpretation for heavier targets(68).

The other experiments are in qualitative agreement with the hypothesis of an expanding and cooling source :

- i) for the 25 MeV/u O+Au system, the pp correlation function leads to a radius of 4 fermis for the emitting zone. If a selection is made on the protons energy, it is found that this radius varies : the higher the energy, the smaller the emitting zone (figure 20).

This is an indication that high energy protons are emitted first, by a very localized and very excited source, whereas low energy protons come later from a larger volume(70).

A radius of 6 to 8 fermis has been deduced from the d-d correlations(69). Here again, the variation of  $r$  with the nature of the correlated particles is in agreement

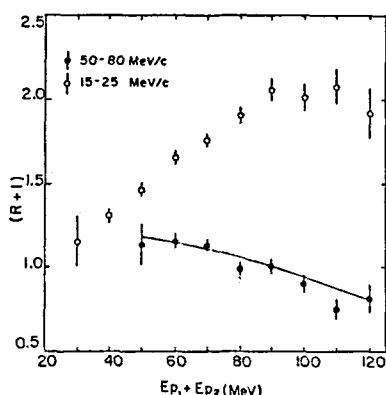


FIGURE 20 :  $p$ - $p$  correlation function gated on relative momentum intervals of 15/25 and 50/80 MeV/c, plotted as a function of the sum energy of the two protons(70).

with an expanding source : the  $d$ - $d$  cross section is larger than the  $p$ - $p$  one, so when the emitting zone expands, its density crosses first a value for which the proton proton interaction stops and later a lower value for which the deuteron deuteron stops ; then the radius measured from  $d$ - $d$  correlations is expected to be larger than that deduced from  $p$ - $p$  correlations (freeze out model(66)).

ii)  $\alpha$ - $d$  correlations have been measured in the 35 MeV/u N+Au system(71). Several particle-unstable resonances are observed :  ${}^6\text{Li}^*$  (2.186 MeV),  ${}^6\text{Li}^*$  (4.31 MeV) and  ${}^6\text{Li}^*$  (5.65 MeV), allowing a joint determination of the radius  $r$  and the temperature  $T$  of the emitting zone. The variation of  $r$  and  $T$  with the kinetic energy of the  $\alpha$ - $d$  couple detected at 50 degrees is shown

in the following table :

Constraint on $E_\alpha + E_d$	T MeV	r Fermi
55/100 MeV	4	3.8
100/150 MeV	6	2.9
150/220 MeV	9	2.6

These results are consistent with particle emission from a subsystem which is in the process of cooling and expanding.

The temperatures determined in this experiment ( $T \sim 5$  MeV) are notably lower than that obtained from single particle inclusive cross sections (15 to 20 MeV)(83) and considerably higher than that deduced from the measurement of ground and long lived resonant states relative production ( $T < 1$  MeV)(84). These discrepancies can be qualitatively understood(71) :

- the single particle inclusive spectra are sensitive to collective motion ;
- the determination of  $T$  from ground and particle-stable resonant states may be biased by feeding of the ground state from higher lying states.

iii) The 60 MeV/u Ar+Au reaction has been studied at GANIL. The experimental set up included :

- an array of 13 telescopes arranged in closed packed geometry for small relative angle correlations ;
- a set of 8 telescopes situated at large angles ;
- the forward plastic wall of 96  $\Delta E$  scintillators, triggered either by two particle coincidences in the telescopes or by scaled down single events.

The spatial extension and the temperature of the emitting source have been determined for several light particle pairs and correlated with the plastic wall multiplicity. The more striking results are the following :

- using the  $\alpha$ - $d$  production, a source radius of 5.5 fermi (figure 19) and a temperature of  $\sim 5$  MeV (figure 21) are found(79,74).

The precision on the determination of the parameter  $T$  can be improved in comparing the production ratio of widely separated levels such as  ${}^5\text{Li}$  (ground state)  $\rightarrow \alpha$ - $p$  and  ${}^5\text{Li}^*$  (16.7 MeV)  $\rightarrow d$ - ${}^3\text{He}$  or  ${}^8\text{Be}^*$  (2.4 MeV)  $\rightarrow \alpha\alpha$  and  ${}^8\text{Be}^*$  (17.6 MeV)  $\rightarrow p$ - ${}^7\text{Li}$ .

The first couple of resonances leads to  $T = 4.6 \pm 0.7$  MeV, the second one to  $T = 4.2 \pm 0.5$  MeV(76).

- The  $\alpha$ - $d$  correlation function varies rapidly with the multiplicity in the plastic wall(78,80) ; the  $r$  parameter increases from 4.5 to 8 fm when the multiplicity goes from 0 to 15 (figure 22).

In spite of the limited solid angle subtended by the multidetector, it can be proved that low measured multiplicities are rather associated with large impact parameters while large measured multiplicities characterize central collisions(80).

The variation of  $r$  with the impact parameter which has already been found at higher energy(82) (figure 23), may reflect simply the variation of the spatial extent of the emitting system. But another interpretation has also been proposed : in the  $r$  determination the life time  $t$  of the heated zone is always forced to be zero. Would  $t$  be

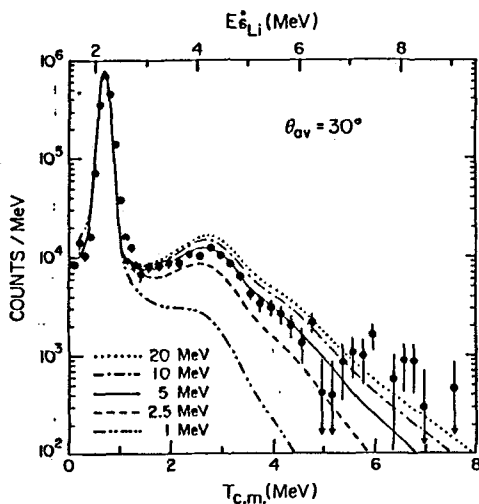


FIGURE 21 : Temperature measurement from  $\alpha$ -d resonant states production in the 60 MeV/u Ar+Au reaction(74).

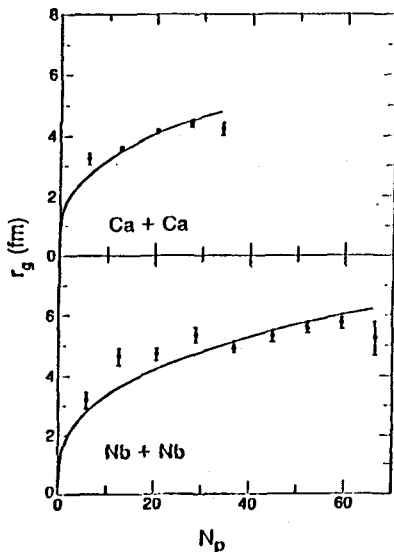


FIGURE 23 : Source radius as a function of proton multiplicity  $N_p$  for the two systems Ca+Ca and Nb+Nb at 400 MeV/u(82).

de further information about the dynamical and geometrical aspects of the collision, such as :

- nuclear shadowing effects(86) ;
- hydrodynamic compression(87) ;
- bounce-off effects(88) ;

In the 25 MeV/u O+Au reaction, light particles are preferentially emitted in the entrance channel scattering plane(54,89), with equal probabilities to be found either

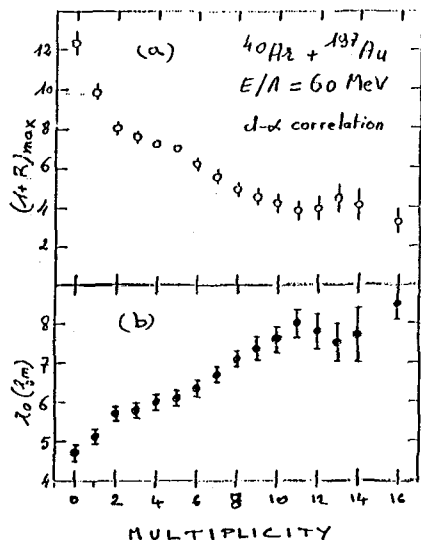


FIGURE 22 : Evolution as a function of the forward light particle multiplicity in the 60 MeV/u Ar+Au reaction(80) of various d- $\alpha$  correlation parameters : a) maximum of the correlation function ; b) space parameter  $r$  in Fermi.

allowed to vary, one could keep  $r$  almost independant of the multiplicity (see figure 17b for an example of  $r$ ,  $t$  correlation). Thus, an alternative explanation of the results of fig. 22 could be that the radius of the emitting system is roughly constant, but the characteristic emission time is proportional to the collision time associated with each impact parameter value. From the data of the plastic wall, collective variables, often used at higher energy, such as transverse momentum or 'thrust value(85)', can be built and correlated with the interferometry parameters(79). It appears that at 60 MeV/u,  $r$  is less sensitive to these collective variables than to the crude multiplicity.

### III-3 : Large angle correlations

Particle particle correlations have also been measured for large relative momenta, outside the range of applicability of the interferometry technique. They can provide

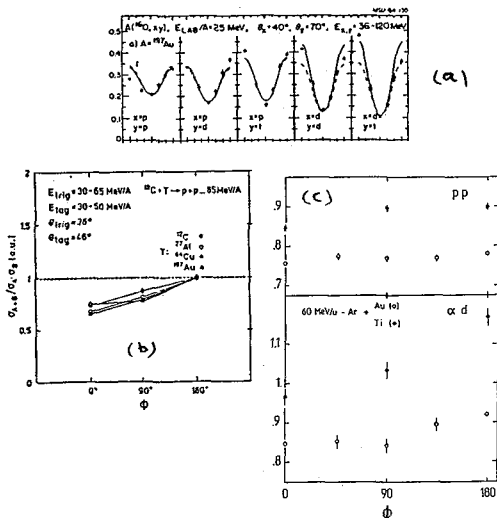


FIGURE 24 : Variation of large angle light particles coincidence rate with the relative azimuthal angle for different systems :

- a) O+Au at 25 MeV/u(54)  
 b) C+various targets at 85 MeV/u(81)  
 c) Ar+Au (o) and Ar+Ti (●) at 60 MeV/u(73)

on the same side or to opposite sides with respect to the beam. These results can be explained by a rotating source model and by the interplay between nuclear shadowing and momentum conservation effects. However, an experiment made on the 85 MeV/u C+Au system has given different results : the p-p and d-d correlation functions vary monotonically with the azimuthal angle and present only a smooth back peaking(90,81) (figure 24).

At 60 MeV/u, the results are rather similar to those of the 85 MeV/u experiment : except for the pp correlation with a gold target (which is flat), the correlation functions increase monotonically from  $\phi=0^\circ$  to  $\phi=180^\circ$ , the slope being steeper for heavier particles and lighter target. This behaviour can be qualitatively understood by the phase space constraints imposed by momentum conservation.

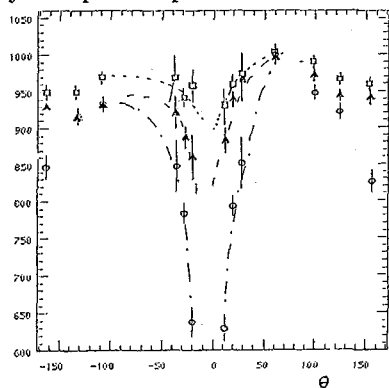


FIGURE 25 : Large in-plane angle correlations for pp pairs produced in the 60 MeV Ar+Au system.

One of the protons is detected at a fixed angle of  $-70^\circ$ ,  $\theta$  is the detection angle of the second proton. Three windows in the plastic wall multiplicity have been defined :

- - - Multiplicity between 0 and 3
- . - Multiplicity between 4 and 6
- .... Multiplicity larger than 6

but due to a lack of statistics and to

The last figure shows the in plane large angle proton proton correlation functions obtained in the 60 MeV/u Ar+Au system. These functions have been calculated for several windows of the light particles multiplicity. A striking result is the presence of a multiplicity dependant minimum in the beam direction. No definitive explanation has been proposed to explain the existence of this minimum.

#### III-4 : Conclusions on particle-particle correlations :

The interferometry ideas provide a nice and fascinating framework for the interpretation of small relative momentum particle particle correlations. Experiments conducted on different systems, at different energies and with different couples of particles lead to rather coherent results on :

- the radius  $r$  of the emitting zone
- its temperature  $T$
- the evolution of  $r$  with the nature of the correlated particles and with the impact parameter of the collision.

However a number of questions and problems remain , such as :

- the correlation method allows in principle a joint determination of both parameters  $r$  and  $t$ , mathematical problems, the spatial extent of the emitting zone is always determined in the hypothesis of a zero life time. How sensitive

is  $r$  to the real value of  $t$  and could the variations of  $r$  as a function of other parameters reflect actually variations of  $t$  ?

- How can we reconcile the idea of temperature with the hypothesis of a very short (if not zero) life time of the heated zone ?

- Uncoherent emission of light particles by the emitting zone is assumed to extract the spatial parameter  $r$  from the correlation function. If some coherent emission is admitted (for example  $^2\text{He}$  or  $^6\text{Li}^*$ ), what is now the meaning of the correlation function and how is the  $r$  determination affected ?

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